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14. ABSTRACT

Analysis of high resolution hydrographic and current data revealed that the Korea Strait Bottom Cold Water (KSBCW) flowed into the Korea Strait from May to January and contained two temperature minimums, one in August/September and another in December/January. With the main current flows confined within 70 km of the Korean coast, maximum southwestward bottom currents corresponded with the temperature minimums. Time-series of bottom current and temperature near the Korean coast clearly showed that the bottom temperature decreased as the bottom current strengthened. Seasonal variation of the KSBCW was linked to the combined effects of the barotropic and baroclinic current variations in the Korea Strait. The annual minimum bottom temperature of the KSBCW was associated with the maximum southwestward baroclinic component. The KSBCW had a secondary maximum southwestward bottom current and secondary minimum temperature in December/January when the Tsushima Warm Current (TWC), flowing into the East/Japan Sea (EJS), had the minimum volume transport.

15. SUBJECT TERMS

current measurement; KSBCW; bottom temperature; temporal variations; Korean Coast

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Seasonal variation of the Korea Strait Bottom Cold Water and its relation to the bottom current

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[1] Analysis of high resolution hydrographic and current data revealed that the Korea Strait Bottom Cold Water (KSBCW) flowed into the Korea Strait from May to January and contained two temperature minimums, one in August/September and another in December/January. With the main current flows confined within 70 km of the Korean coast, maximum southwestward bottom currents corresponded with the temperature minimums. Time-series of bottom current and temperature near the Korean coast clearly showed that the bottom temperature decreased as the bottom current strengthened. Seasonal variation of the KSBCW was linked to the combined effects of the barotropic and baroclinic current variations in the Korea Strait. The annual minimum bottom temperature of the KSBCW was associated with the maximum southwestward baroclinic component. The KSBCW had a secondary maximum southwestward bottom current and secondary minimum temperature in December/January when the Tsushima Warm Current (TWC), flowing into the East/Japan Sea (EJS), had the minimum volume transport. **Citation:** Kim, Y. H., Y.-B. Kim, K. Kim, K.-I. Chang, S. J. Lyu, Y.-K. Cho, and W. J. Teague (2006), Seasonal variation of the Korea Strait Bottom Cold Water and its relation to the bottom current, *Geophys. Res. Lett.*, *33*, L24604, doi:10.1029/2006GL027625.

1. Introduction

[2] It is interesting that the cold water in the Korea Strait, the Korea Strait Bottom Cold Water (KSBCW), is coldest in summer when the Tsushima Warm Water (TWW) in the upper layer is warmest [*Lim and Chang*, 1969]. Since the first report of the KSBCW by *Nishida* [1926], there have been many studies on its origin [*Lim and Chang*, 1969; *Cho and Kim*, 1998], structure [*Park et al.*, 1995; *Cho and Kim*, 1998] and seasonal variation [*Cho and Kim*, 1998; *Isobe*, 1994].

[3] Previous studies on the KSBCW relied mostly on hydrographic data to show the presence of the KSBCW in the western channel of the Korea Strait only in summer [*Nishida*, 1926; *Lim and Chang*, 1969; *Cho and Kim*, 1998]. However, it should be noted that these studies were based on bi-monthly hydrographic data taken at coarse station separations, which could not fully resolve the temporal variation and spatial structure of the KSBCW. Furthermore, there seems to be some disagreements between hydrographic and current observations. Recently, *Johnson and Teague* [2002] analyzed current data from an array of 13 bottom-mounted Acoustic Doppler Current Profilers (ADCPs) deployed across the Korea Strait from 1999 to 2000 [*Teague et al.*, 2002]. They reported that there was no advective intrusion of the KSBCW on a monthly scale and that the only sustained intrusions occurred in May/June and in December/January from the bottom temperatures observed at the moorings. On the other hand, current data of *Shinozaki et al.* [1996] and *Takikawa et al.* [2005] showed the intrusion of the KSBCW into the Korea Strait all year around except in late winter.

[4] The purpose of this work is: 1) to understand the temporal variation of the KSBCW utilizing historical hydrographic and current datasets with high resolution in time and space and 2) to examine the relation between the temporal variation of the KSBCW and the bottom currents. Details of the data sets analyzed in this work and monthly variation of the KSBCW are presented in section 2. The relationship of the KSBCW to the bottom current follows in section 3. Finally, summary and discussion are given in section 4.

2. Monthly Variation of the KSBCW

2.1. Temperature

[5] Bottom temperatures across the Korea Strait were available from 50 repeaters on a submarine telephone cable between Pusan, Korea and Hamada, Japan from 1982 to 1992 [*Min*, 1994; *Isoda and Oomura*, 1992], which are spaced about every 4 km as shown in Figure 1. Monthly temperature data from 1932 to 1942 taken by the Central Fisheries Research Station (CFRS) and bi-monthly hydrographic data from 1970 to 2001 by the National Fisheries Research and Development Institute (NFRDI) (Figure 1) were analyzed. Both hydrographic data of the CFRS and NFRDI were obtained at standard depths and near the bottom in the Korea Strait.

[6] Mean bottom temperatures from 50 repeaters follow the bathymetry on the whole as shown in Figure 2a. Mean bottom temperature decreased from R3 to have a minimum at R7 as the depth increased and reached another minimum at R10 located near the second maximum depth. Defining here the KSBCW as the water where temperature is lower than 10°C following *Lim and Chang* [1969] and *Cho and Kim* [1998], the KSBCW appears only west of R12, implying that its main path is confined in the western part

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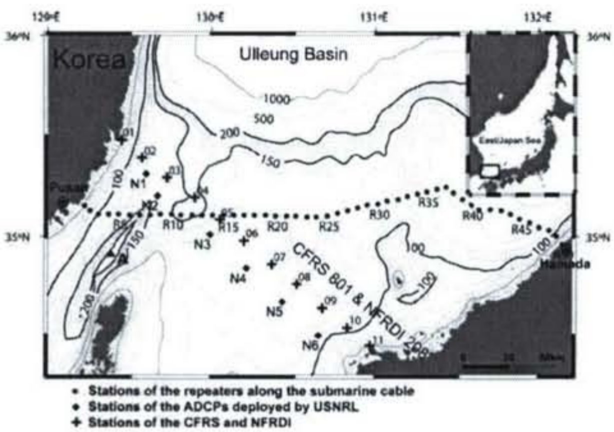

Figure 1. Location of the repeaters along the submarine cable, the ADCPs and the hydrographic stations. Solid lines indicate depth of the bottom in meters. Station A represents the deepest point on the observation line of the ferryboat Camellia [*Takikawa et al.*, 2005].

of the Korea Strait. Therefore, the bottom temperatures in the western part will be analyzed primarily henceforth.

[7] Mean bottom temperatures of most repeaters in the western part, shown in Figure 2b, decrease from April or May but the temperature at R7 decreases from March. R4 to R8 (referred to as the western trough hereafter) have minimum temperatures in August, when the TWW is generally warmest in the upper layer [*Lim and Chang*, 1969; *Cho and Kim*, 1998]. However, the low bottom temperatures between 7.5°C and 8.5°C persist from August to February at R10 to R12 (referred to as the eastern trough hereafter).

[8] Besides the presence of the KSBCW in summer, which is very well known [*Lim and Chang*, 1969; *Cho and Kim*, 1998], this paper particularly focuses on an additional but warmer temperature minimum colder than 10°C which appears also in January (hereafter, referred to as the second minimum) in the vicinity of the western trough. Bottom temperatures begin to increase from August, they tend to decrease in November or December. In addition, time-series of bottom temperatures from 1982 to 1991 indicates that the KSBCW developed in December/January as well as in summer almost every year around the western trough (not shown).

[9] Monthly variation of the mean bottom temperatures shows that the temperature minimums around the western trough except at R7 are compatible with or lower than those around the eastern trough in summer even though the depths of the repeaters in the western trough except at R7 are shallower than those around the eastern trough (Figure 2b). Furthermore, the bottom temperatures around the western trough rapidly decrease from spring to summer. However, the second temperature minimums in the western trough, except at R7, are much higher than temperatures in the eastern trough. Such spatial distribution of the bottom temperature minimums can be closely related with the characteristic spatial structure of the KSBCW, which will be discussed later.

[10] Vertical sections of monthly mean temperatures for February, March, April, August, and January along CFRS Line 801 (Figure 3) show the spatial structure of the KSBCW. The KSBCW is present year-round, with the maximum extent in August and January. In February to April, the KSBCW shrank and the cold water less than 10°C was observed only at the bottommost data bin.

[11] The KSBCW was found on the sloping bottom toward the Korean coast in the western channel of the Korea Strait within 70 km of the coast. Bottom temperatures were generally lowest at Station 2 or 3. While the KSBCW has been known to retreat in winter [*Lim and Chang*, 1969; *Cho and Kim*, 1998], it appeared until January in the vertical temperature sections along CFRS Line 801. The 10°C isotherm extended further offshore from December to January as its western end became deeper.

2.2. Intrusion of the KSBCW

[12] Together with the hydrographic data, current data are important to confirm the southwestward intrusion of the KSBCW into the Korea Strait. Thirteen bottom-mounted ADCPs with temperature sensors were deployed across the Korea Strait in two legs; Leg I from May 1999 through mid-October 1999 and Leg II from mid-October 1999 through

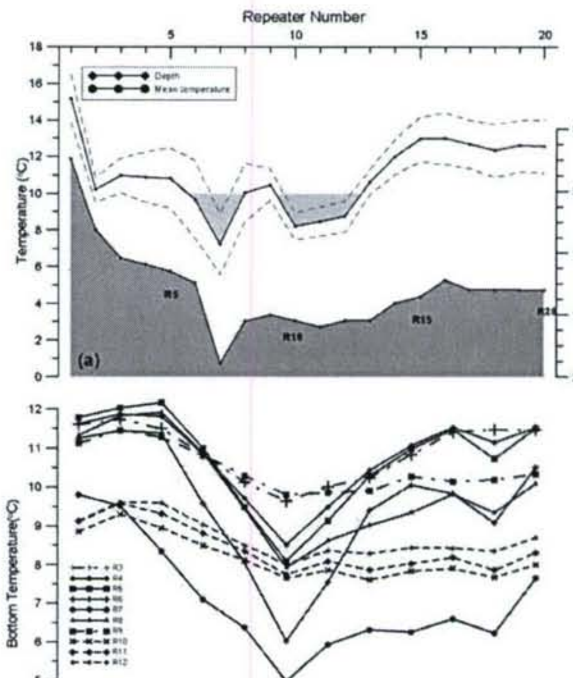

Figure 2. (a) Depth and mean bottom temperature at R1 to R20 along the submarine cable; dashed lines denote the range of the standard deviations from the mean bottom temperatures and mean bottom temperatures less than 10°C are shaded. (b) Climatological monthly mean bottom temperature from R3 to R12 from 1982 to 1992; solid/dashed line correspond to repeaters in the western/eastern trough.

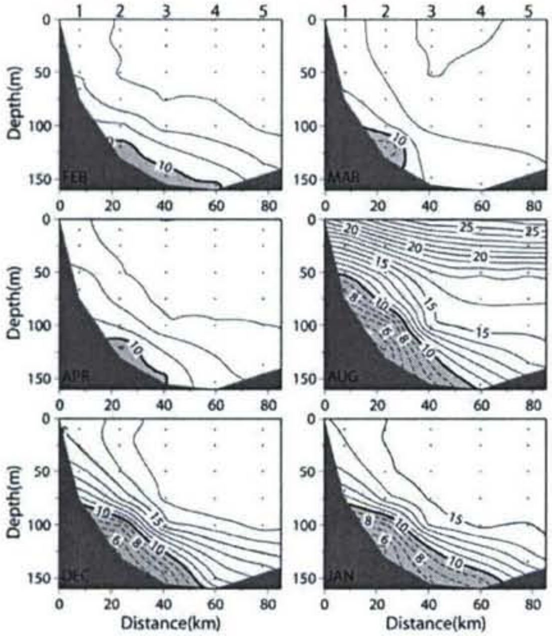

Figure 3. Vertical sections of the climatological monthly mean temperatures on the CFRS line 801 from 1932 to 1942. Distance starts from the Korean coast.

March 2000 [*Perkins et al.*, 2000; *Teague et al.*, 2002; *Johnson and Teague*, 2002]. Mooring N1 could not be recovered at the end of Leg I but was redeployed and returned good data for Leg II. Moorings N2-N6 returned good data for both legs.

[13] Special attention is paid to currents and bottom temperatures at mooring N1 of Leg II which is located along the main path of the KSBCW according to the vertical temperature sections of the CFRS (Figure 3). A low-pass filter with a half-power period of 40 hours was applied to remove tidal and inertial variability of the temperatures and currents. The currents at mooring N1 were compared with transports estimated from voltage differences across the submarine telephone cable [*Lyu and Kim*, 2003; *Kim et al.*, 2004] to further analyze relationship between the KSBCW intrusion and the transport variation.

[14] The time series of currents (Figure 4) at Mooring N1 clearly shows the southwestward intrusion of the KSBCW just above the bottom from November 1999 to mid-February 2000. The intrusion is confined in a thin layer of 10–30 m above the bottom, which makes it difficult to observe by other means. The maximum speed of the along-strait component of the intrusion was over 15 cm/sec.

[15] The bottom temperature measured simultaneously becomes colder when the current becomes stronger during the intrusion (Figure 4). The maximum southwestward intrusion of the KSBCW during Leg II is also consistent with the minimum bottom temperature in December/January. Little discussion has been made on the relation between the movement and temperature of the KSBCW in previous studies [*Shinozaki et al.*, 1996; *Cho and Kim*, 1998; *Takikawa et al.*, 2005] because there have been no current and temperature data simultaneously measured near the bottom in the Korea Strait.

3. Relation Between the Variation of the KSBCW and the Bottom Current

[16] The along-strait current component (v) in the Korea Strait can be expressed as the sum of the barotropic (v_t) and the baroclinic (v_c) components and is given by $v = v_t(x, t) + v_c(x, z, t)$. The depth-average of the baroclinic component is zero by definition and the baroclinic component can be estimated from the horizontal density gradient by the thermal wind equation assuming geostrophic balance. The along-strait current at the bottom can also be expressed as the sum of the barotropic and baroclinic components given by

$$v(x, -H, t) = v_t(x, t) + v_c(x, -H, t),$$

where H is the depth of the bottom.

[17] Climatological monthly mean barotropic and baroclinic components of along-strait currents at the bottom and absolute bottom currents are shown in Figure 5. The barotropic component was derived from the monthly mean current taken by vessel-mounted ADCP from February 1997 to August 2002 [*Takikawa et al.*, 2005] in the deepest trough (station A, Figure 1) of the western channel while the baroclinic component was calculated from the climatological mean hydrography between stations 2 and 3 of NFRDI 208 (Figure 1), similar to CFRS 801. Though station A is located about 50 km southwest from station 2 and 3 of NFRDI 208, both of them are along the path of the KSBCW from the temperature sections of CFRS 801 (Figure 3) and 901 (not shown).

[18] The barotropic component is directed toward the East/Japan Sea (referred to as EJS hereafter) all year round with a maximum in October and a minimum in January,

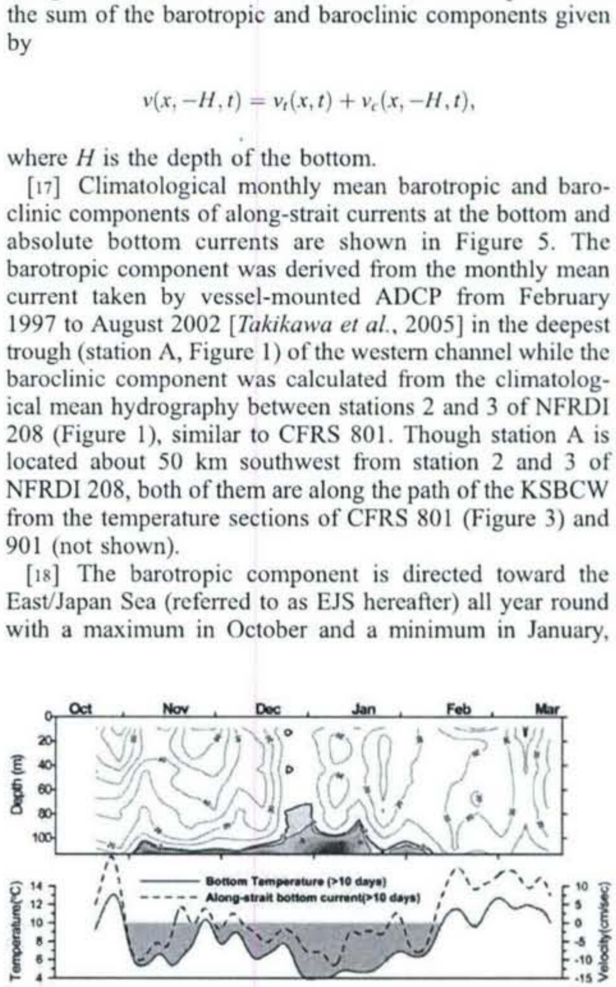

Figure 4. Time series of the along-strait component of (top) the velocity and (bottom) the bottom temperature and along-strait bottom current measured at the lowest observation depth at station N1 from October 1999 to March 2000. The velocity was averaged every 10-days and positive values represent flow toward the EJS from the Korea strait while negative values (shaded) represent flow into the strait from the EJS. A low-pass filter with half-power period of 10 days was applied to the bottom temperature (solid) and along-strait bottom current (dashed). Shaded values indicate less than 10°C for the bottom temperature and toward the Korea Strait from the EJS for the bottom current.

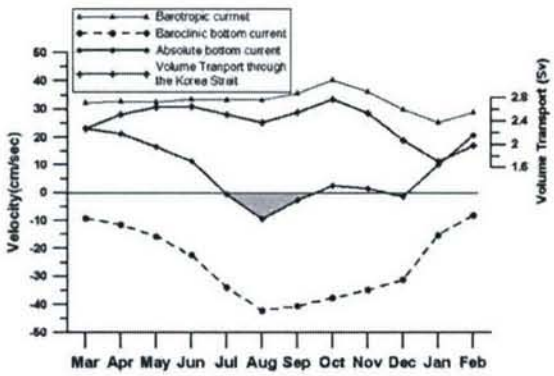

Figure 5. Climatological monthly mean of the along-strait barotropic current (triangles), baroclinic bottom current (circles), absolute bottom current (diamonds, as sum of the barotropic and baroclinic components) and volume transport through the Korea Strait (pluses) by the submarine cable from 1998 to 2002. The barotropic current was calculated at the deepest trough (station A) from *Takikawa et al.* [2005] and the baroclinic current was calculated from the hydrography from the NFRDI. Negative absolute current means southwestward and are shaded.

which is coincident with those of the volume transport through the Korea Strait (Figure 5) [*Kim et al.*, 2004; *Takikawa et al.*, 2005]. The baroclinic component at the bottom is directed toward the Korea Strait from the EJS with a maximum strength in August and then decreases until March (Figure 5).

[19] Along-strait bottom current, estimated as the sum of barotropic and baroclinic components, reveals the occurrence of maximum southwestward intrusions of the KSBCW in August and December, which are consistent with two minimums of bottom temperature around the western trough near the Korean coast though the second minimum temperature appeared in January (Figure 2). Although the absolute bottom current in December is small, it reaches 10 cm/sec southwestward when the baroclinic current shear is extended from the bottommost available data at 125 m depth to the actual bottom depth of about 150 m.

[20] The baroclinic component of the along-strait bottom current has a southwestward maximum in August and then decreases gradually. In addition, the barotropic component decreases from October to January. The decrease rate of the barotropic component is larger than the decrease rate of the baroclinic component from October to December, which results in the maximum southwestward along-strait bottom current in December (Figure 5).

[21] The southwestward bottom current in December was also found in currents measured by bottom-mounted ADCPs (Figure 4). The baroclinic current decreased as the vertical density structure became homogeneous in winter, and hence the barotropic component dominated the temporal variation of the KSBCW. During Leg II, the barotropic component at mooring N1 was highly correlated with the volume transport with the statistical coherency higher than 0.8 for periods longer than 10 days (not shown). The bottom current at mooring N1 was also significantly correlated with the volume transport with the coherency higher than 0.7 for periods longer than 10 days with little phase lag (not shown). The high correlation supports the assumption that the bottom cold water intrudes when the volume transport decreases [*Johnson and Teague*, 2002]. Weakening of the KSBCW in October/November and enhancement in December/January corresponded to the maximum transport of the TWC in October and the minimum transport in December/January, respectively (Figure 5) [*Lyu and Kim*, 2003; *Kim et al.*, 2004; *Takikawa et al.*, 2005].

[22] In August, the maximum southwestward total current is due to the maximum baroclinic component. The baroclinic component dominates the bottom current in the Korea Strait so that the barotropic component alone could not explain the temporal variation of the KSBCW in summer (Figure 5).

4. Summary and Discussion

[23] The highly-resolved hydrographic and current data revealed that the KSBCW intruded from May to January with two minimum bottom temperatures and two corresponding maximum southwestward bottom currents in August/September and December/January, respectively. While the intrusion of the KSBCW in summer has been well documented, the occurrence of the second minimum temperature and maximum bottom current of the KSBCW in December/January is newly identified in this study. Historically, the KSBCW has been known to retreat in winter [*Lim and Chang*, 1969, *Cho and Kim*, 1998] implying no intrusion. However, this study shows that direct current measurement confirms that it flows into the Korea Strait from November, 2000 to next mid-February. Furthermore, temperature data show the existence of the KSBCW from May to January, indicating that the KSBCW flows into the Korea Strait almost all year round except February to April.

[24] Temporal variations of the KSBCW resulted from the combined effects of baroclinic and barotropic flow responses in the Korea Strait. In winter, measured bottom currents in the Korea Strait were highly correlated with the volume transport of the TWC. This high correlation suggests that the barotropic response dominates the temporal variation of the KSBCW in winter as vertical stratification weakens. The second maximum intrusion of the KSBCW was concomitant with the minimum transport of the TWC in December/January.

[25] The North Korean Cold Current (NKCC) has been identified as the cold current flowing southward underneath the northward East Korean Warm Current along the eastern coast of Korea extending to the Korea Strait [*Kim and Kim*, 1983; *Cho and Kim*, 1998]. Reports have been given of the strengthening of the NKCC in summer, which might be associated with the observed maximum baroclinic bottom current in the Korea Strait in summer. Further studies about the relationship between the KSBCW and the NKCC with their variability are required to better understand the temporal variation of the KSBCW, especially in summer.

[26] The main path of the KSBCW is confined within 70 km of the Korean coast and the KSBCW tended to hug the Korean coast with isopycnals sloping upward toward the Korean coast [*Park et al.*, 1995; *Cho and Kim*, 1998]. The spatial structure of the KSBCW exhibits a seasonal varia-

tion. The slope of isopycnals associated with the KSBCW intrusion becomes sharper in summer than in winter. It is difficult to observe the seasonal variation of the KSBCW particularly during summer if observations are not made close to the Korean coast [*Johnson and Teague*, 2002]. In addition, the second minimum temperature of the KSBCW could rarely be resolved in the previous hydrographic datasets with coarse resolution in time. High resolution data in both space and time are required to measure the KSBCW and to understand its dynamics.

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